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TECHNICAL NOTE

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EFFECT OF GROUNDBOARD HEIGHT ON THE AERODYNAMIC CHARACTERISTICS OF A LIFTING CIRCULAR CYLINDER USING TANGENTIAL BLOWING FROM SURFACE SLOTS FOR LIFT GENERATION

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SUMMARY

A wind-tunnel investigation has been made to determine the ground effect on the aerodynamic characteristics of a lifting circular cylinder using tangential blowing from surface slots to generate high lift coefficients. The tests were made on a semispan model having a length 4 times the cylinder diameter and an end plate of 2.5 diameters. The tests were made at low speeds at a Reynolds number of approximately 290,000, over a range of momentum coefficients from 0.14 to 4.60, and over a range of groundboard heights from 1.5 to 10 cylinder diameters.

The investigation showed an earlier stall angle and a large loss of lift coefficient as the groundboard was brought close to the cylinder when large lift coefficients were being generated. For example, at a momentum coefficient of 4.60 the maximum lift coefficient was reduced from a value of 20.3 at a groundboard height of 10 cylinder diameters to a value of 8.7 at a groundboard height of 1.5 cylinder diameters. In contrast to this there was little effect on the lift characteristics of changes in groundboard height when lift coefficients of about 4.5 were being generated. At a height of 1.5 cylinder diameters the drag coefficients generally increased rapidly when the slot position angle for maximum lift was exceeded. Slightly below the slot position angle for maximum lift, the groundboard had a beneficial effect, that is, the drag for a given lift was less near the groundboard than away from the groundboard. The variation of maximum circulation lift coefficient (maximum lift coefficient minus momentum coefficient) obtained in this investigation is in general agreement with a theory developed for a jet-flap wing which assumes that the loss in circulation is the result of blockage of the main stream beneath the wing.

INTRODUCTION

Present-day interest in the recovery of rocket boosters has led to the exploration of unconventional methods for recovery. One method which might be applicable to long cylindrical types involves the generation of lift on a circular cylinder with its axis normal to the relative air flow. This concept utilizes the full length of the cylinder as a high-aspect-ratio lifting surface and involves the reorientation of the vehicle prior to landing. Two recent investigations have shown that considerable lift can be generated on a circular cylinder without the L
necessity of rotating the cylinders. One method (ref. 1) uses a small 1
flap on the bottom surface to induce circulation; the other method 5
(ref. 2) is an adaptation of the jet flap principle. With the latter 2
method a gas is ejected tangentially from a spanwise slot along the 1
upper surface. This induced circulation can result in lift coefficients of considerable magnitude. For example, one of the slot configurations studied in reference 2 gave a lift coefficient of 25 for a blowing momentum coefficient of 6. From experience gained with the jet-augmented flap of reference 3, it would be expected that these large lift coefficients might be materially reduced when in the presence of the ground. The purpose of this investigation was to determine the effect of ground on the aerodynamic characteristics of a lifting cylinder using ejected air to generate lift.

The investigation was made on a semispan model having a length of 4 diameters and an end plate of 2.5 diameters. The blowing configuration (3 slots 45° apart) was one of the better ones tested in reference 2. The model was tested through maximum lift coefficient at several heights above the groundboard, at various momentum coefficients, and for a range of slot angular positions.

SYMBOLS

C_D drag coefficient, $\frac{\text{Drag}}{q_u S}$

C_L lift coefficient, $\frac{\text{Lift}}{q_u S}$

$(C_L)_{max}$ maximum lift coefficient for a given cylinder height and momentum coefficient

C_{L_Γ} circulation lift coefficient, $(C_L)_{max} - C_\mu$

C_μ momentum coefficient, $\frac{T}{q_u S}$

C_m pitching-moment coefficient, $0.5C_\mu$

q free-stream dynamic pressure, $\rho V^2/2$, lb/sq ft

S projected area of cylinder, sq ft

T thrust reaction of slots, lb

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V free-stream velocity, ft/sec

ρ mass density of air, slugs/cu ft

δ reference-slot position, relative to undisturbed airstream, deg (see fig. 2)

$\delta_{(C_L)_{max}}$ reference-slot position for maximum lift coefficient

d cylinder diameter, in.

h height of cylinder axis above groundboard, in.

A cross-sectional area, sq ft

Subscripts:

o test section without groundboard

u upper channel of test section with groundboard

l lower channel of test section with groundboard

max maximum

MODEL AND APPARATUS

The investigation was made in the Langley 300-MPH 7- by 10-foot tunnel with the tunnel ceiling used as a reflection plane. A diagram of the model and groundboard installation is presented in figure 1. The standard mechanical balance system was used to measure the lift and drag. Compressed air which was used as a blowing medium was brought onto the balance system through a long $1\frac{1}{2}$-inch-diameter steel pipe.

The method used for connecting the pipe with the balance system provides little or no tares.

The semispan cylinder used in the investigation had a diameter of 6 inches, a length of 24 inches, and an end plate of 15 inches at the outboard end. At the inboard end where the cylinder protruded through the tunnel wall, a small end plate was attached to reduce the spanwise flow. The pressurized cylinder was equipped with three full-span 0.006-inch slots spaced 45° apart as shown in figure 2. The 0.006-inch measurement is an average value obtained when the slot was inoperative; actual measurements varied from 0.005 to 0.0075 inch. (No gap measurements were made with the slots under pressure.) Air was supplied to the slots through a series of 1/16-inch holes on 1/2-inch centers as shown in figure 2.

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The groundboard used in the investigation completely spanned the tunnel test section and extended approximately 10 diameters upstream and downstream of the cylinder axis. The groundboard height, as determined from the cylinder axis to the groundboard, was varied from 9 inches ($h/d = 1.5$) to 33 inches ($h/d = 5.5$). For a part of the investigation the groundboard was removed; the sidewall then represents the groundboard in which case the value of h/d is 10.

TEST CONDITIONS

The use of the groundboard in the tunnel complicates the measurement of the dynamic pressure over the model by dividing the tunnel test section into two channels. Model blockage could possibly reduce the flow above the groundboard and conversely the blowing could increase the flow above the groundboard making direct measurement of the average dynamic pressure difficult. The standard tunnel instrumentation can be used, however, to calculate the total flow rate in the tunnel. This information together with a knowledge of the average velocity beneath the groundboard makes it possible to calculate the average dynamic pressure about the cylinder. Therefore, a survey was made beneath the groundboard for every groundboard height to determine a position of a pitot static tube which would give an average dynamic-pressure reading. The dynamic pressure above the groundboard (about the cylinder) was then calculated by the following relationship for every data point obtained:

$$q_u = \left(\frac{A_o}{A_u}\sqrt{q_o} - \frac{A_1}{A_u}\sqrt{q_1}\right)^2$$

where q refers to the dynamic pressure and A the cross-sectional areas of the respective sections. The subscripts u, l, and o are used to designate the upper channel, lower channel, and the reference conditions (tunnel without groundboard), respectively. The investigation was made at a Reynolds number of approximately 290,000 based on a cylinder diameter of 0.500 foot.

The momentum coefficient is based on the thrust reaction at the slots as determined from the measured torque about the cylinder axis. The reaction was assumed to occur on the surface of the cylinder; therefore, the outside radius of the cylinder was used in computing the thrust. Calibrations of thrust against a reference pressure were made outside of the tunnel on a special balance in order to obtain greater accuracy than that of the tunnel balance system.

RESULTS AND DISCUSSION

The basic data showing the effect of groundboard height on the lift and drag characteristics of the cylinder are presented in figure 3. The groundboard height parameter h/d refers to the distance between the cylinder axis and the top of the groundboard measured in cylinder diameters. For convenience, the data for the cylinder without groundboard are plotted at a value of $h/d = 10$, the distance the cylinder is from the tunnel sidewall.

Pitching-moment data are not presented; however, the pitching-moment coefficients C_m can be estimated from the relationship $C_m = 0.5C_\mu$.

The lift data show, as would be expected from the jet-flap data near the ground (ref. 3), a considerable loss in lift when large lift coefficients are generated in the presence of the groundboard. For example, at $C_\mu = 4.6$, the maximum lift coefficient is reduced from a value of 20.3 at $h/d = 10$ to a value of 8.7 at $h/d = 1.5$. (See fig. 3(e).) In contrast to this the lift coefficient at a $C_\mu = 0.14$ (fig. 3(a)) is only slightly reduced as the groundboard is moved closer to the cylinder. It is interesting to note that there are no significant changes in lift-curve slope except that which occurs in the immediate vicinity of maximum lift coefficient. The maximum lift coefficients are shown as a function of groundboard height in figure 4. Also included in figure 4 is the reference angle δ at which maximum lift was obtained. The angle δ for $(C_L)_{max}$ in general becomes smaller as the groundboard height is reduced.

The maximum lift coefficients are again presented in figure 5 as a function of momentum coefficient. These data show increasing values of

$(C_L)_{max}$ with C_μ and also show that the rate of increase of lift coefficient with momentum coefficient decreases as the momentum coefficient increases. The points at which the rate of increase of lift coefficient with momentum has a slope value of 1.0 have been indicated on the curves of figure 5 by a tick. These results suggest that the circulation lift has reached a maximum for the groundboard heights under consideration. These maximum values of circulation lift coefficients can be approximated by assuming that the total momentum coefficient is acting in a lift direction. The circulation lift coefficient would then be the difference between the total lift coefficient and the momentum coefficient as indicated in the following equation:

$$C_{L_\Gamma} = (C_L)_{max} - C_\mu$$

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The circulation lift coefficient given by the preceding equation has been replotted in figure 6 as a function of momentum coefficient. These values are the lower limit of circulation lift that can be obtained since it is assumed that the jet sheet is discharged normal to the relative wind (jet deflection angle 90°). Angles of jet-sheet deflection other than 90° would result in higher values of circulation lift coefficient as C_μ in the preceding equation would be replaced by C_μ times the sine of the jet deflection angle. It is believed, however, that the full momentum coefficient should be used in calculating C_{L_Γ} since experience with jet flaps (ref. 4) has shown that the maximum lift coefficient occurs when the jet sheet leaves the wing approximately normal to the free airstream.

The maximum values of circulation lift coefficient $\left(C_{L_\Gamma}\right)_{max}$ determined from the faired curves of figure 6 have been replotted in figure 7 as a function of groundboard height. It is noted that the ground effect on the circulation lift coefficient is very large since decreasing the groundboard height from $h/d = 5.5$ to $h/d = 1.5$ reduced $\left(C_{L_\Gamma}\right)_{max}$ from 12.5 to 5.5. This effect has been noted previously with jet-flap wings. (See ref. 3.) Several theoretical studies have been made to predict the loss in lift effect but have met with only partial success. One recent paper on the subject (ref. 5) considers blockage of the main stream between the wing and the ground as the limiting factor in the generation of lift. In reference 5 the author develops an expression for the circulation in terms of the airfoil chord and distance above the ground. This expression has shown good agreement with experimental results for model clearances as low as one-quarter chord. The curve representing this expression is reproduced in figure 7. It is noted that

the experimental values of $\left(C_{L_\Gamma}\right)_{max}$ are in general agreement with the theory developed for the jet-flap wing, particularly at lower values of h/d where the cylinder is close to the groundboard.

The effect of the groundboard on the aerodynamic characteristics of the blowing cylinders is further illustrated in figure 8 where the drag coefficient has been plotted against lift coefficient for the extremes in h/d tested. (The open symbols represent values for $h/d = 1.5$ and the solid symbols represent values for $h/d = 10.0$.) Also included are reference slot angles δ which are indicated by the dashed line. In addition to the loss of lift noted previously, the data near the groundboard ($h/d = 1.5$) generally show large increases of drag coefficient when the angle δ for maximum lift coefficient is exceeded. Slightly below the angle for maximum lift coefficient the cylinder near the groundboard gave less drag for a given lift than that away from the groundboard. This beneficial effect is probably due to the lower induced drag which is normal for any wing in the presence of the ground.

A plot of the lift and drag coefficients at the points of intersection of the curves in figure 8 is presented in figure 9 as a function of momentum coefficient. These data show that for $h/d = 1.5$ the lift-coefficient range over which there is no ground effect or a beneficial one (less drag) extends from $C_L = 4.45$ at $C_\mu = 0.14$ to $C_L = 8.7$ at $C_\mu = 4.6$. However, nothing is to be gained in circulation lift above $C_\mu = 1.6$ ($C_L = 6.9$) as the increase in lift and drag coefficient may be accounted for by changes in reaction. Also included in figure 9 is the slot position δ corresponding to the given lift and momentum condition. The difference between δ for the two sets of groundboard data is small, but the range of δ values with momentum coefficient is rather extreme. In a practical application these ranges of δ could be reduced considerably by the operation of single slots of a multiple-slot configuration. Reference 2 shows that one slot is equally as effective as three slots 45° apart; only reorientation of the single slot would be necessary to give equivalent lift and drag.

SUMMARY OF RESULTS

A wind-tunnel investigation was made at low speeds to determine the effect of ground proximity on the aerodynamic characteristics of a cylinder using tangential blowing from surface slots to generate high-lift coefficients. The investigation was made on a circular cylinder having a fineness ratio of 8 and an end plate of 2.5 diameters by using an adjustable board to simulate various distances above the ground. The results are summarized as follows:

1. There was a large loss of lift coefficient and an earlier stall angle as the groundboard was brought close to the cylinder when large lift coefficients were being generated. For example, at a momentum coefficient of 4.6 the maximum lift coefficient was reduced from a value of 20.3 at a height of 10 cylinder diameters to a value of 8.7 at a distance of 1.5 cylinder diameters from the groundboard. In contrast to this there was little effect of groundboard height at a momentum coefficient of 0.14 which developed lift coefficients of approximately 4.5.

2. The variation of maximum circulation lift coefficient (maximum lift coefficient minus momentum coefficient) with groundboard height obtained in this investigation is in general agreement with the theory developed for a jet-flap wing which assumes that the loss in circulation is the result of blockage of the main stream beneath the wing.

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3. At a height of 1.5 cylinder diameters the drag coefficients generally increased rapidly when the slot position angle for maximum lift was exceeded; slightly below the angle for maximum lift the groundboard had a beneficial effect, that is, the drag for a given lift was less near the groundboard than away from the groundboard.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., August 11, 1961.

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2. Lockwood, Vernard E.: Lift Generation on a Circular Cylinder by Tangential Blowing From Surface Slots. NASA TN D-244, 1960.

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5. Huggett, D. J.: An Approach to the Theoretical Study of the Ground Effect on a Jet Flap. Rep. No. F.M. 2695 (Rep. No. A.R.C. 20,279), June 30, 1958.

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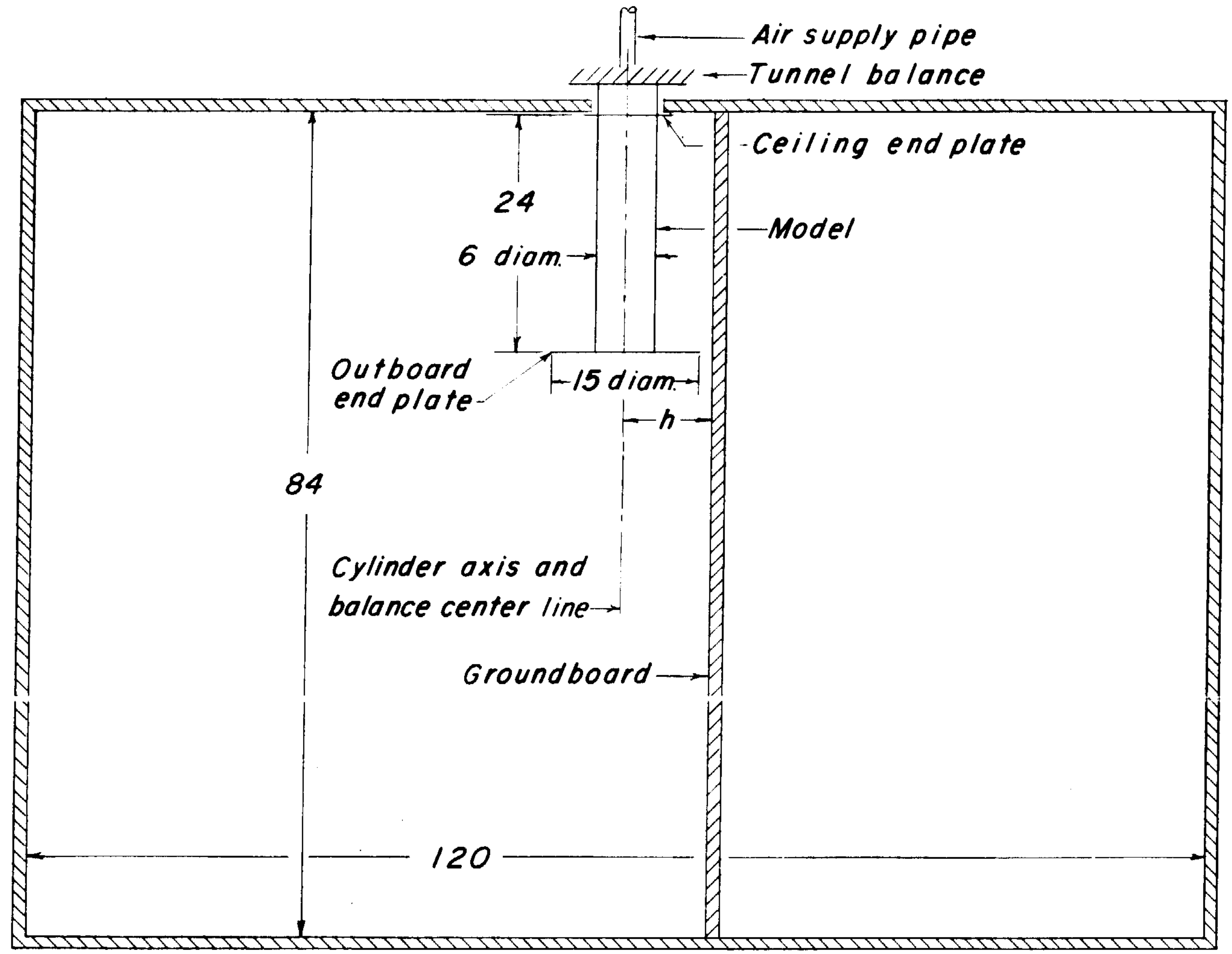

Figure 1.- Diagram of semispan cylinder and groundboard arrangement in the Langley 300-MPH 7- by 10-foot tunnel. Groundboard extended 60 inches upstream and downstream from cylinder axis. All dimensions are in inches.

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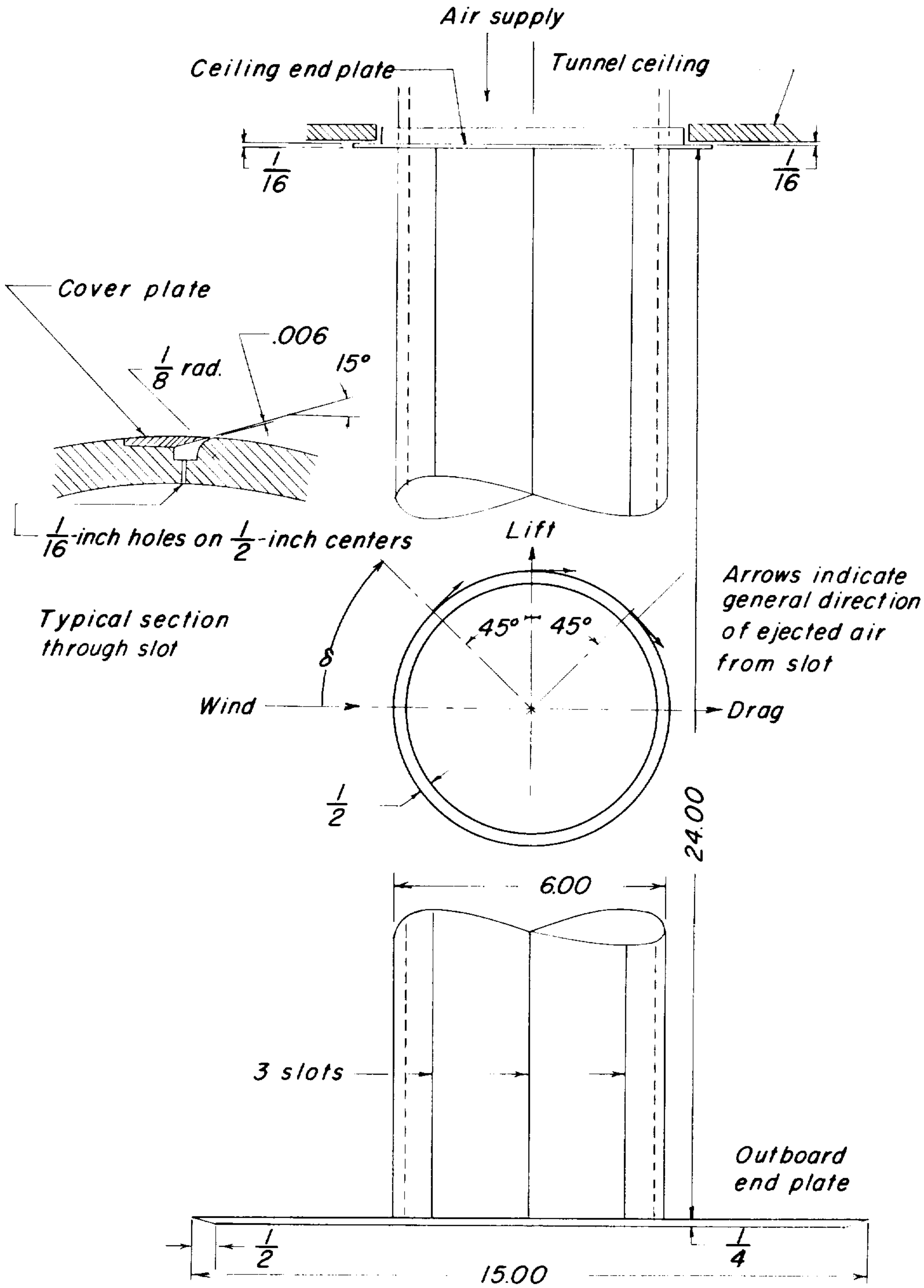
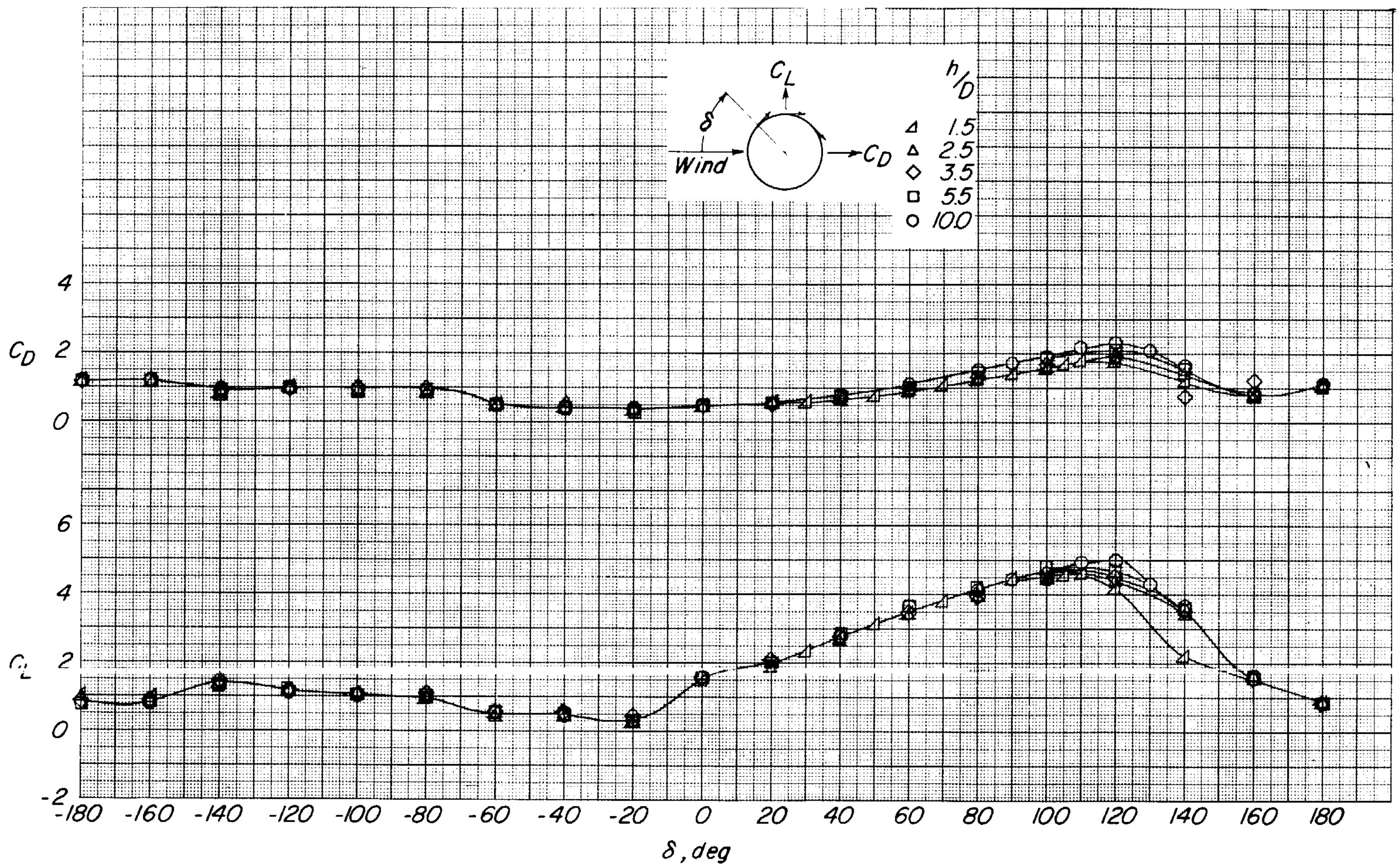


Figure 2.- Details of the semispan cylinder tested. All dimensions are in inches.



(a) $C_\mu = 0.14$.

Figure 3.- Effect of groundboard height on the lift and drag characteristics of the lifting cylinder.

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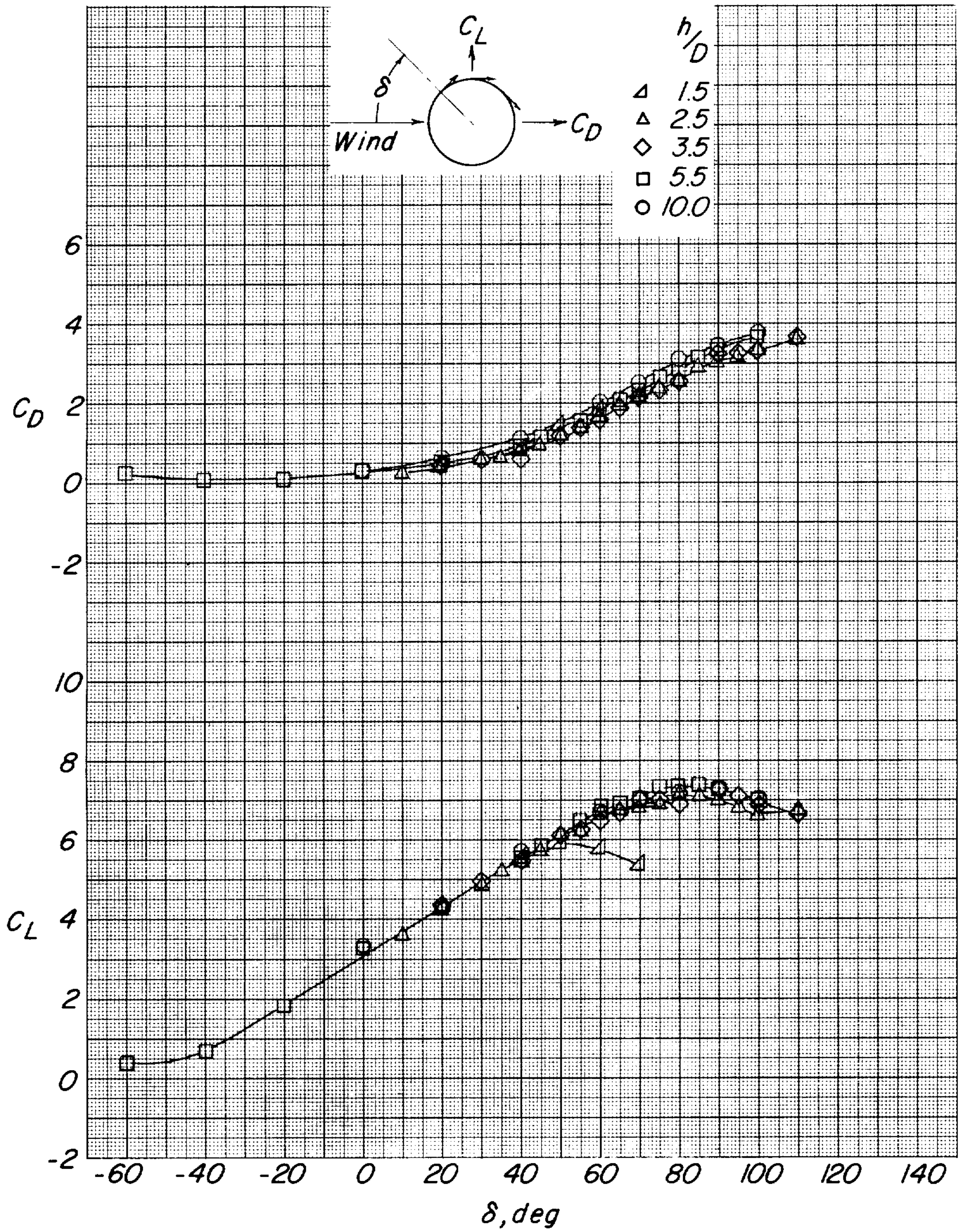
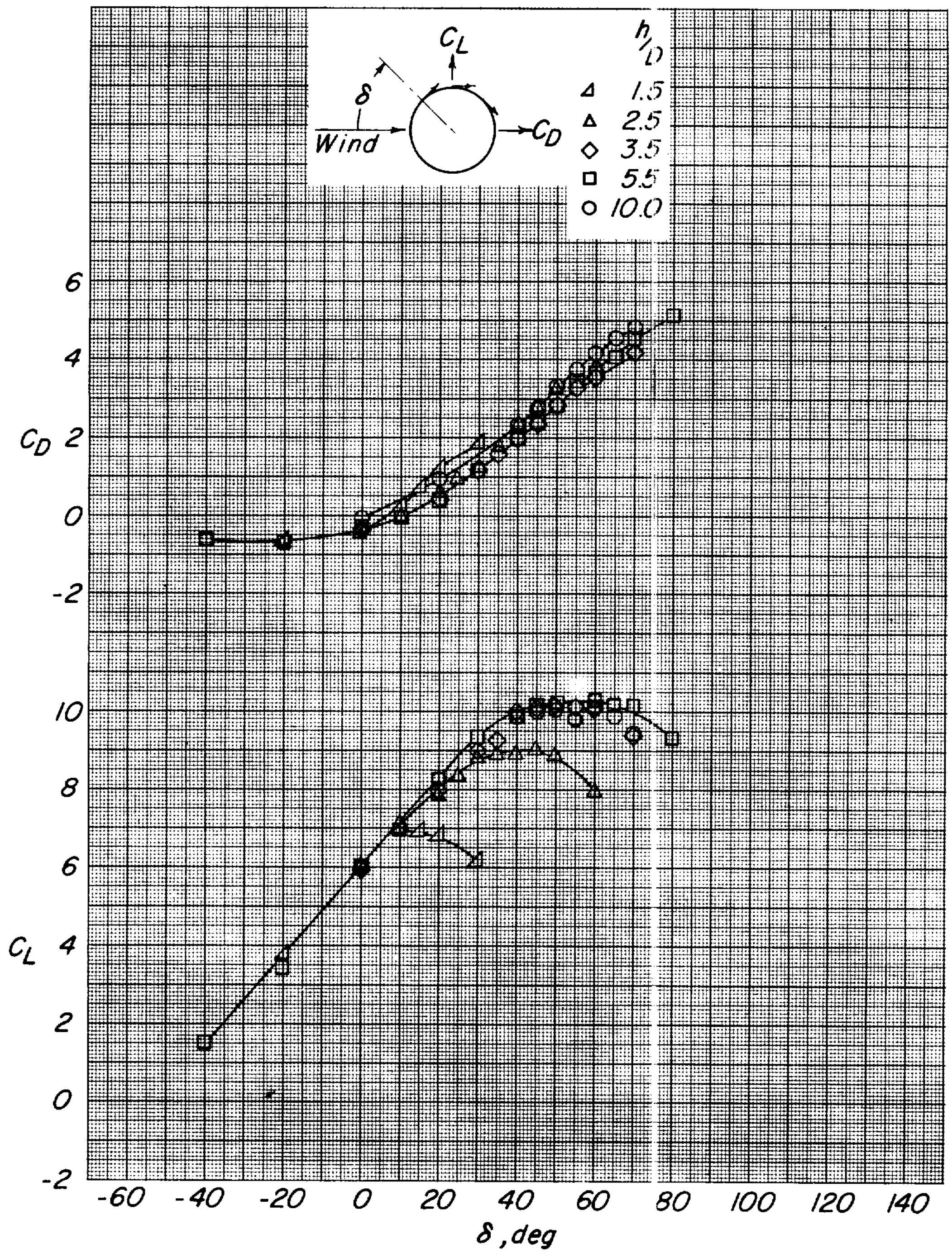


(b) $C_\mu = 0.59$.

Figure 3.- Continued.



(c) $C_\mu = 1.64$.

Figure 3.- Continued.

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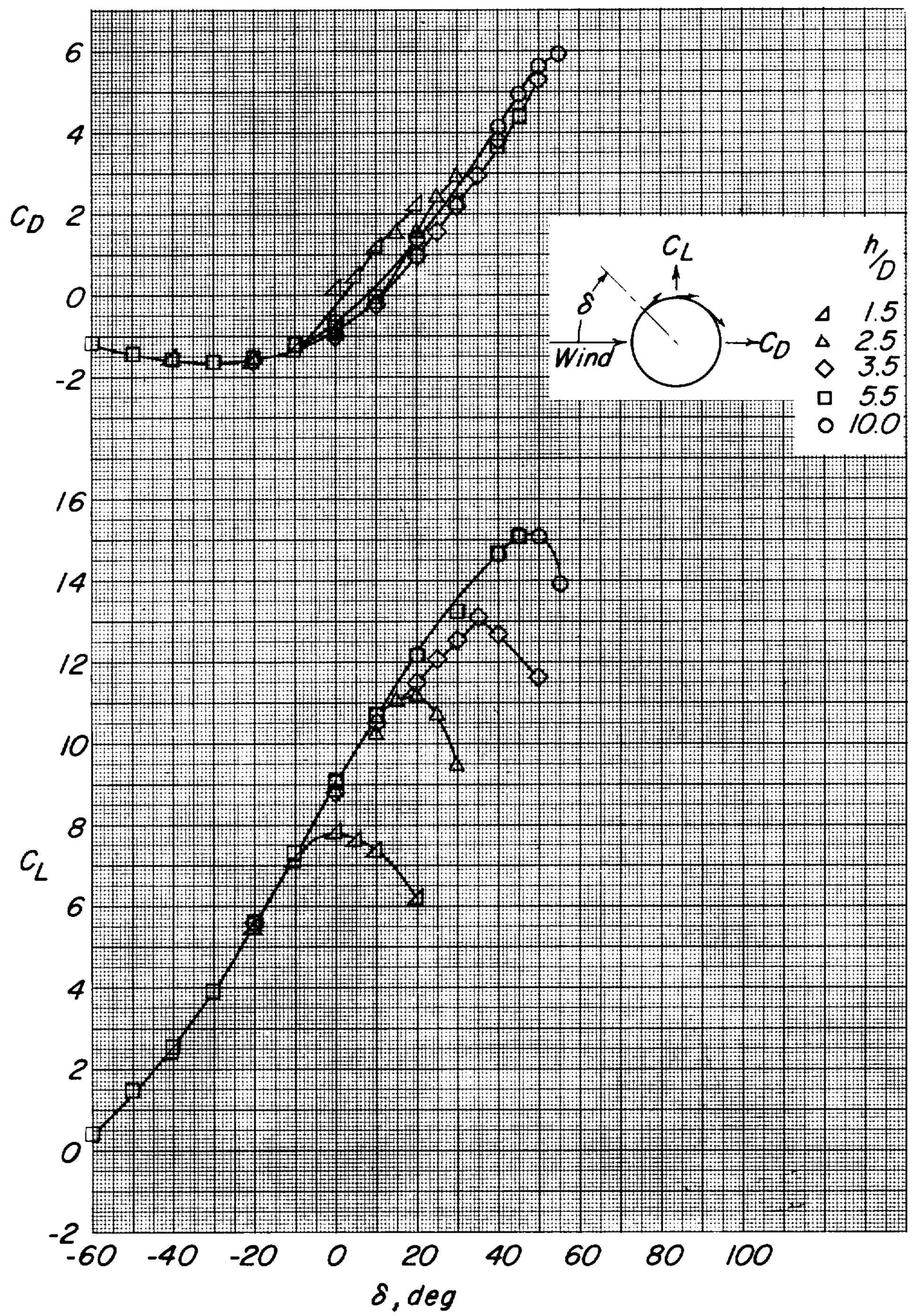
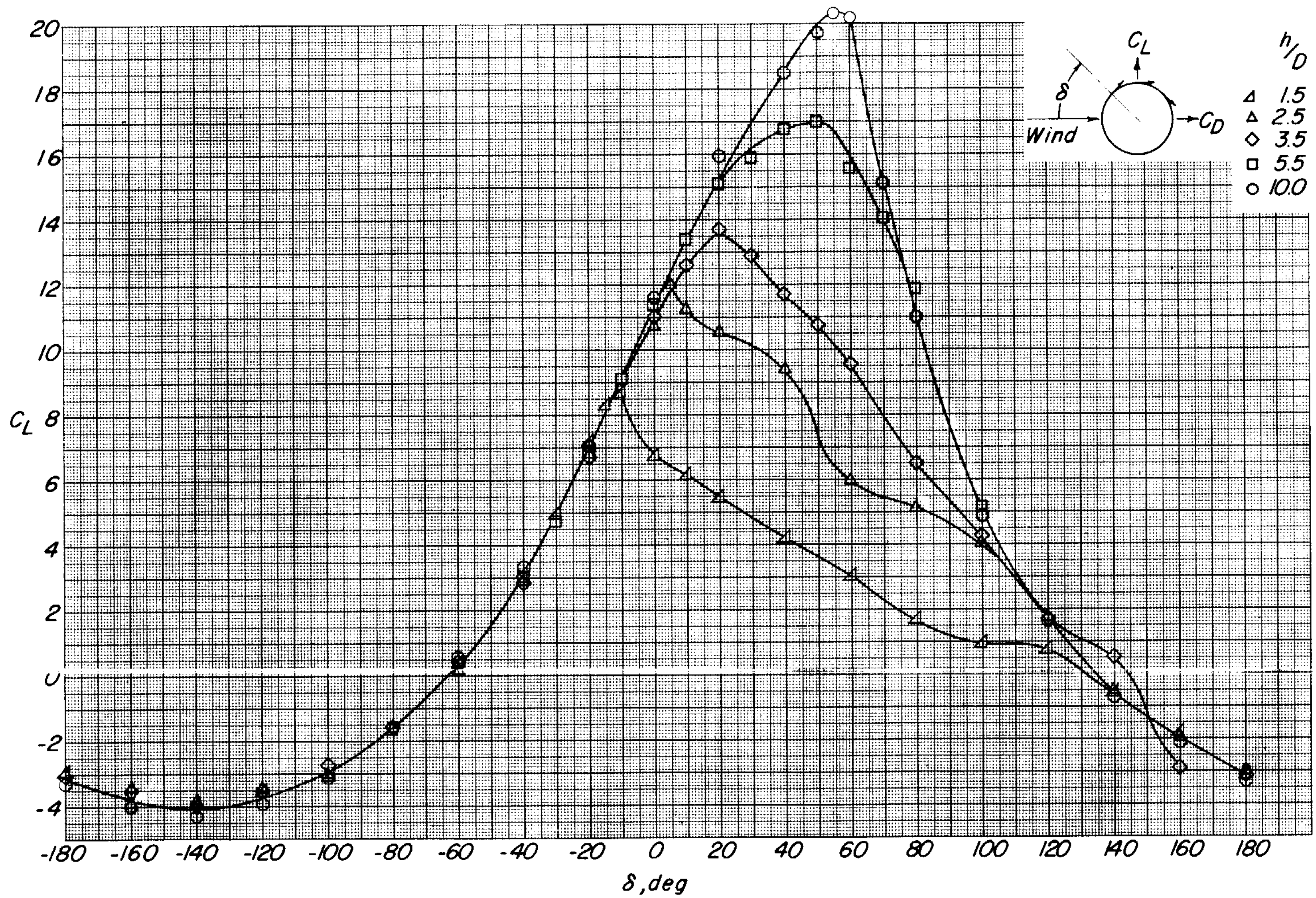


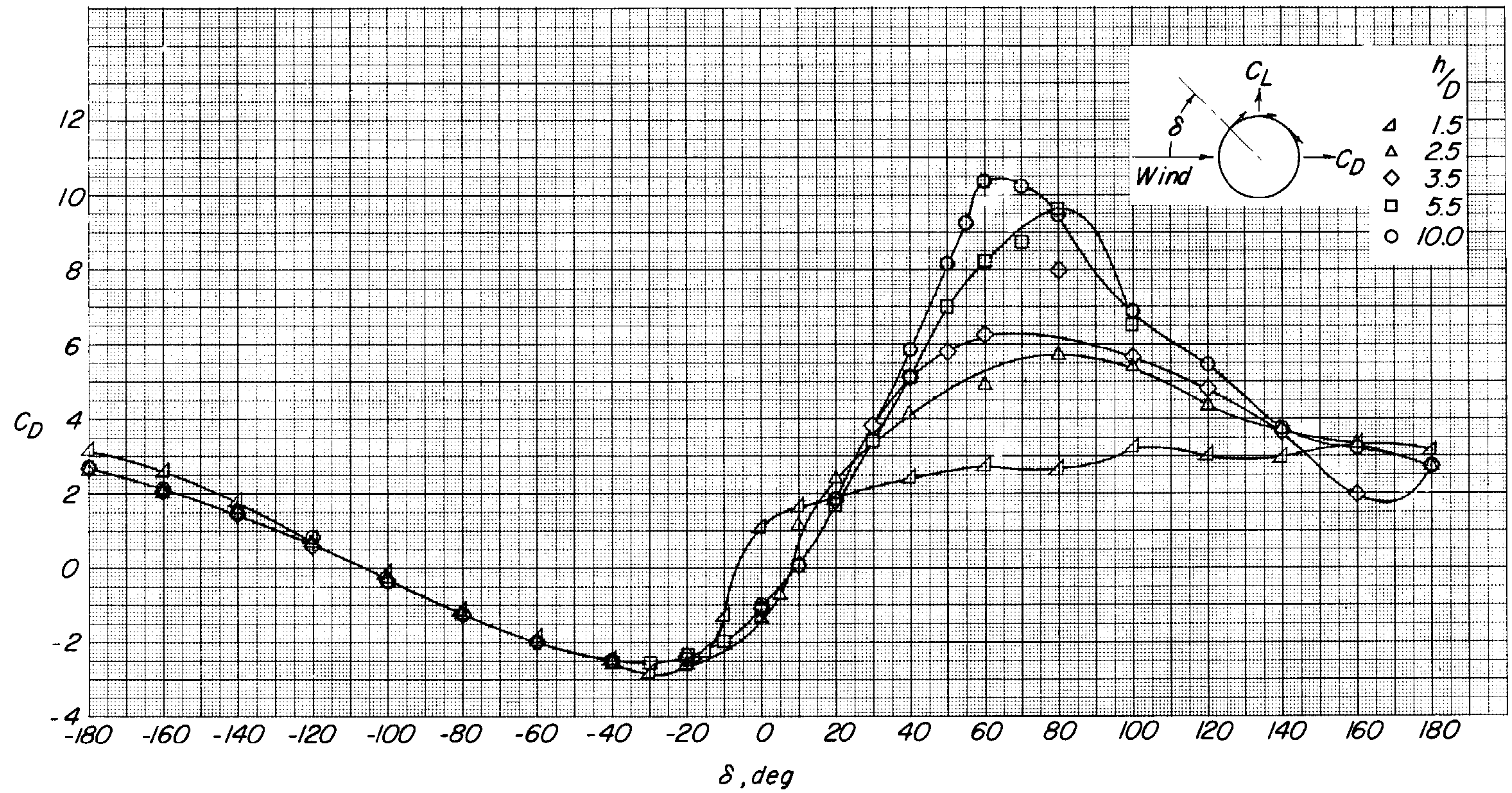
(d) $C_\mu = 3.16$.

Figure 3.- Continued.



(e) $C_\mu = 4.60$.

Figure 3.- Continued.



(e) Concluded.

Figure 3.- Concluded.

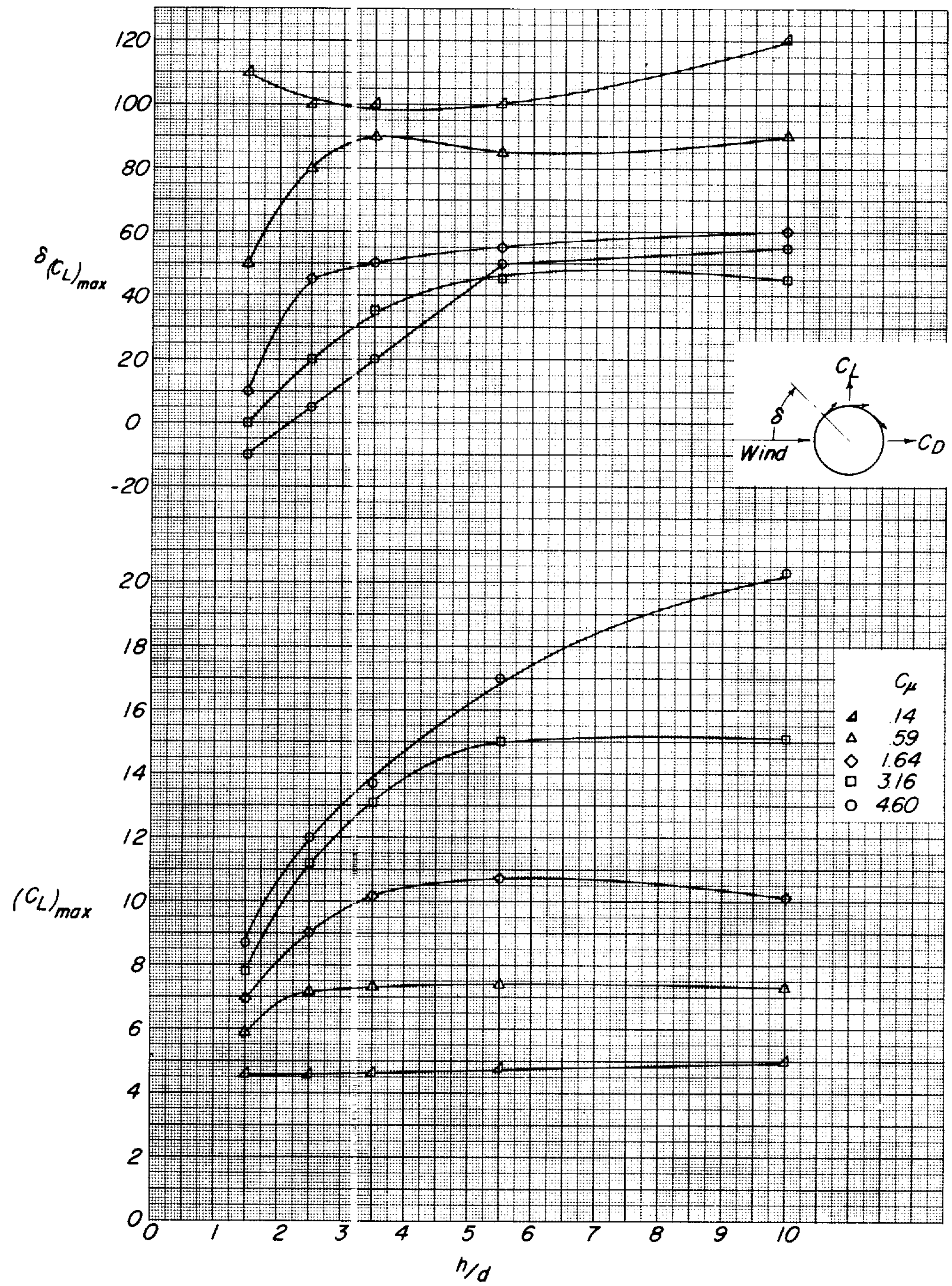


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Figure 4.- Effect of groundboard height and blowing momentum coefficient on the maximum lift characteristics.

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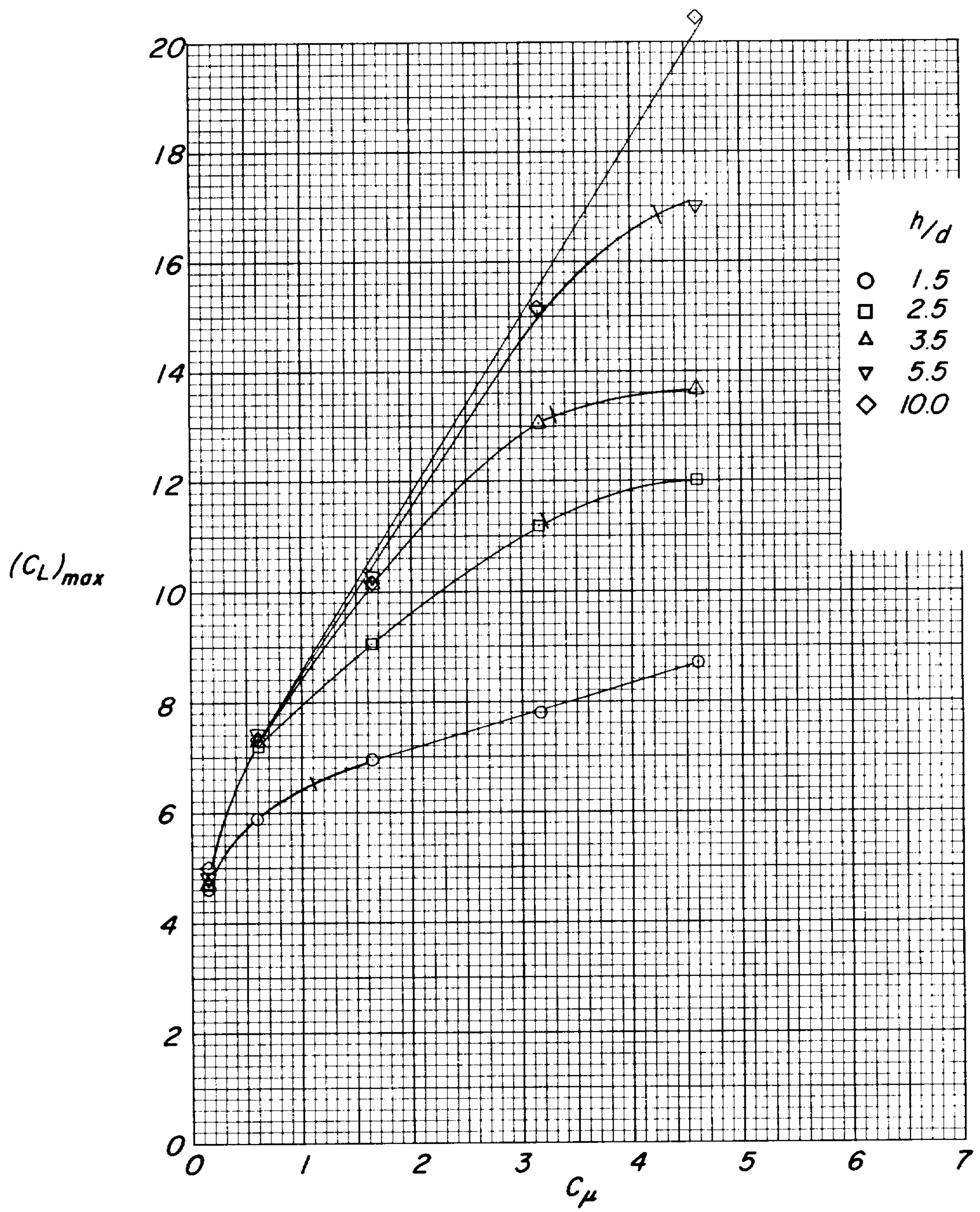

Figure 5.- Variation of $\left(C_L\right)_{max}$ with C_μ. Ticks indicate point at which $\frac{d\left(C_L\right)_{max}}{dC_\mu} = 1$.

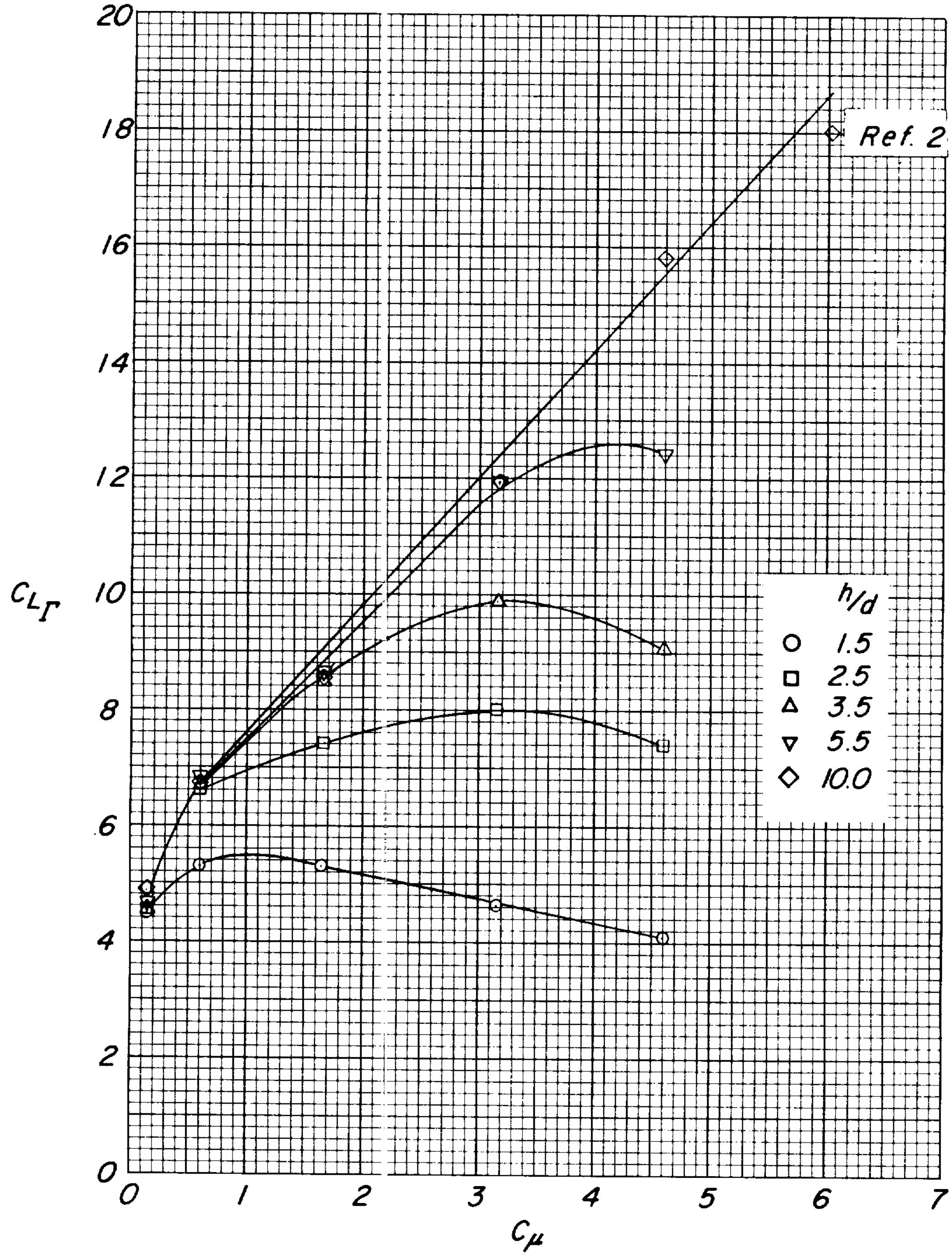

Figure 6.- Variation of C_{L_T} with C_μ.

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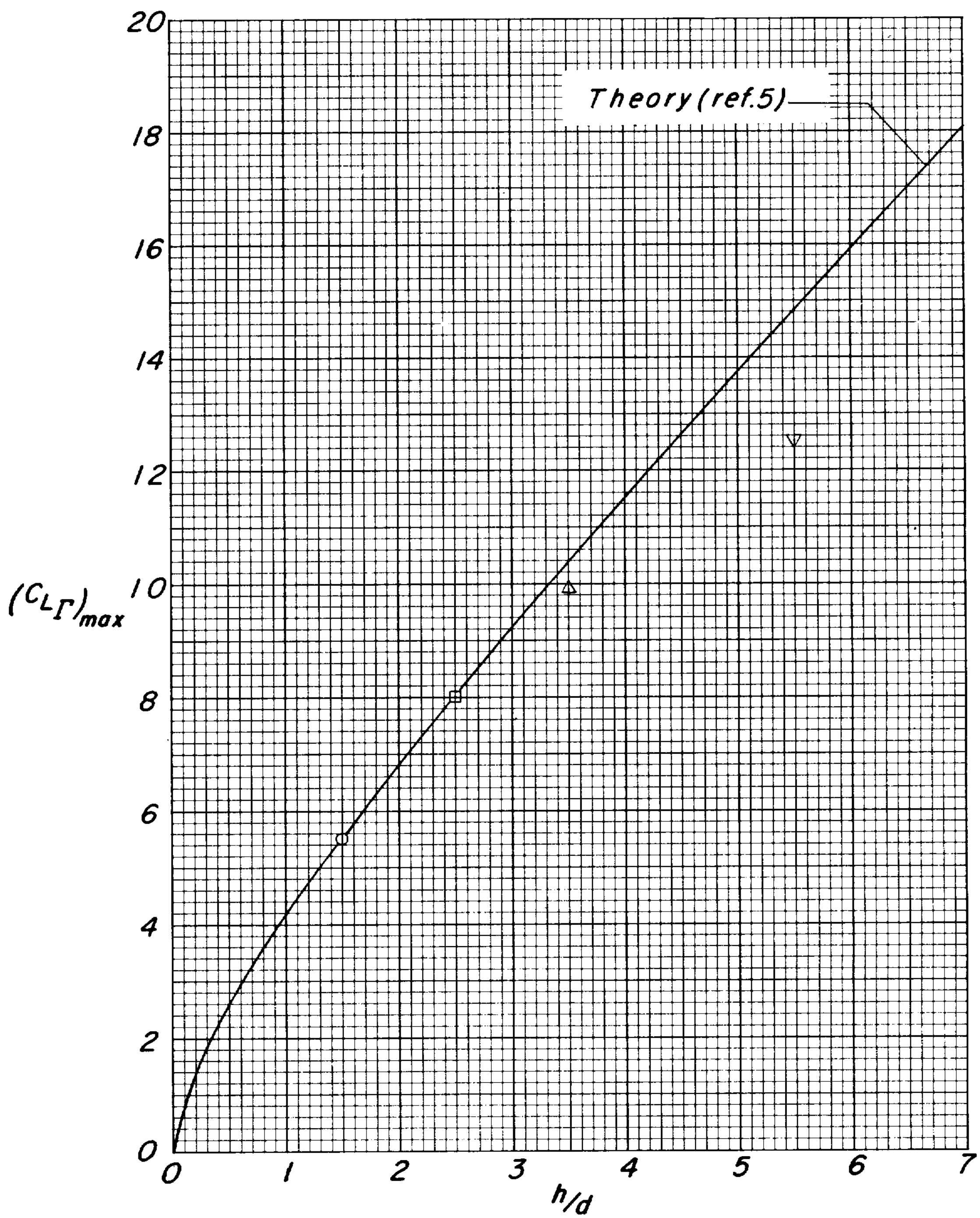

Figure 7.- Comparison of $\left(C_{L_\Gamma}\right)_{max}$ with two-dimensional jet-flap theory. Symbols are for values from faired curves of figure 6.

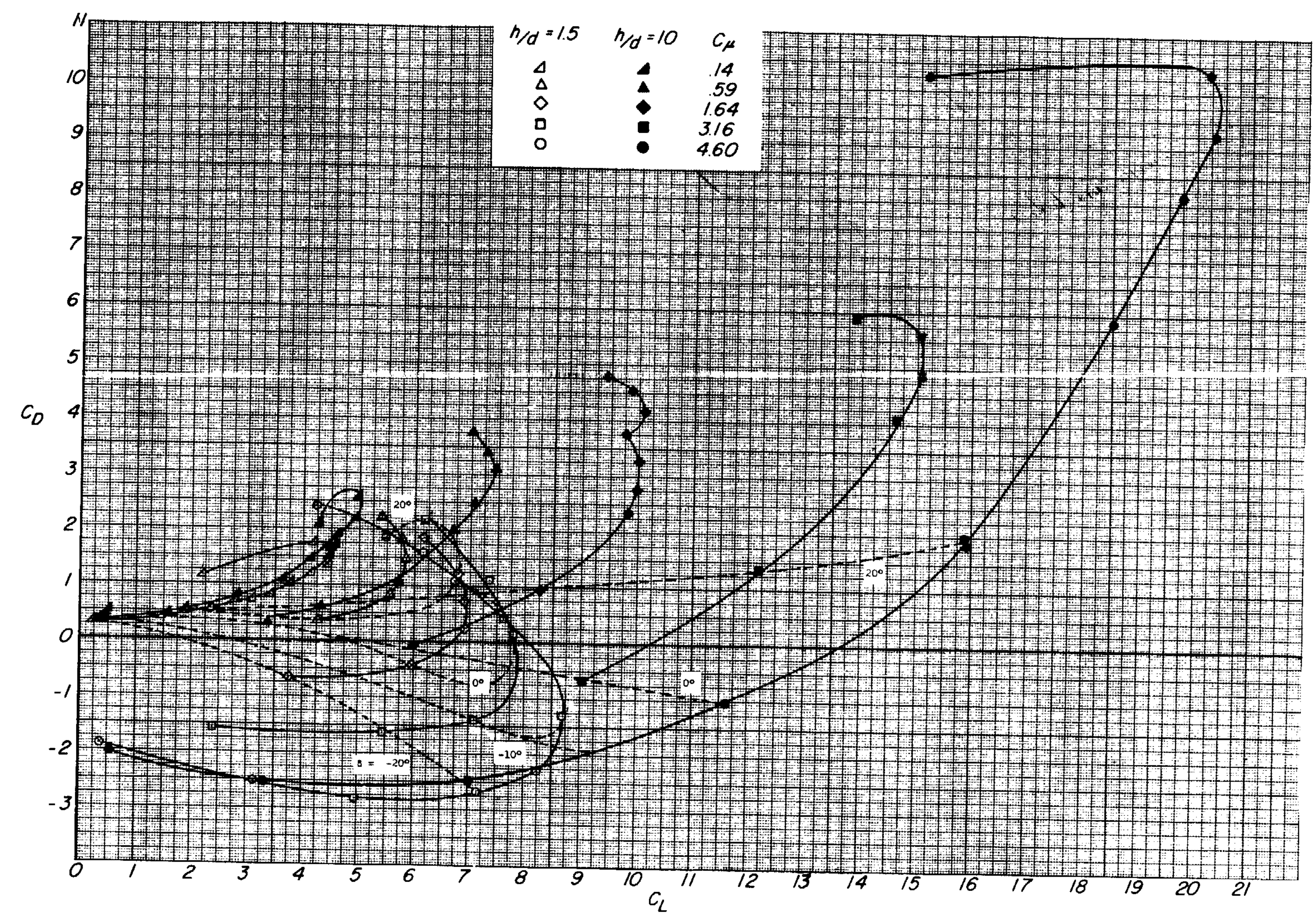

Figure 8.- Variation of drag coefficients with lift coefficients for the cylinder near the groundboard and that away from the groundboard.

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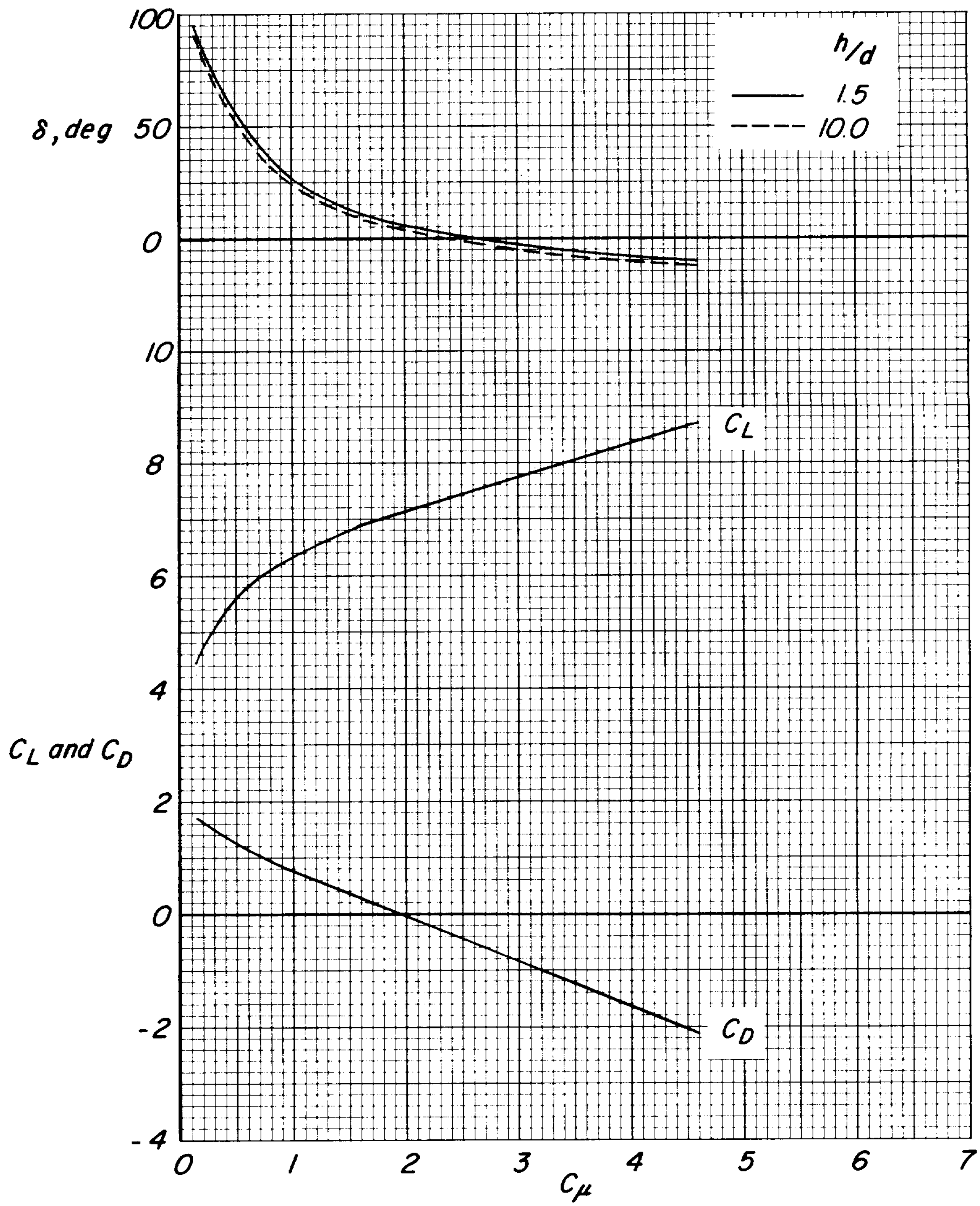

Figure 9.- Limiting values of C_L, C_D, and δ for favorable ground effect.